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PHYSICAL MODELING OF THE GLASS MELT HYDRODYNAMICS IN A HIGHLY EFFICIENT MELTING FURNACE FOR CONTAINER GLASS

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Certain regularities of the motion of glass melt flows in a highly efficient furnace for container glass are studied employing the method of physical modeling of the glass melt hydrodynamics.

Modern practice calls for studying the conditions that ensure production of high-quality glass in highly efficient glass-melting furnaces.

The method of physical modeling [1] allows for a clear picture of mass exchange in a glass-melting furnace and makes it possible to issue recommendations for furnace operation. The present paper describes the glass melt hydrodynamics in the melting tank of the furnace located in the Krasnoe Ékho glass factory.

Technical parameters of the furnace

Type of furnace	Regenerative, with transverse flame direction and with working channels
Glass	Clear glass BT-1
Furnace output, ton/day	200
Surface area, m^2:	
of the melting tank	104.93
of the working channels	18.78
Type of fuel	Natural gas ($Q_n^{calc} = 33$ MJ/m^3 or 7970 kcal/m^3)
Product range	Bottles for various purposes
Type of glass-shaping machines	AL-118-2 (3 machines)
Surface area of entries, m^2	5.86
Fuel consumption for furnace heating, nm^3/h	1801.55
Temperature conditions, °C:	
max. melting temperature	1530
max. working temperature	1220
air heating temperature in regenerator	1100

The rectangular melting tank has a trapezoidal spillover threshold and a sunk clarification and homogenization zone (a deep refiner).

The furnace is equipped with two working channels with independent heating. The melting-tank bottom, including the deep refiner, is heat-insulated by two chamotte layers whose total thickness is 600 mm. The melting-tank walls have continuous chamotte heat insulation. The furnace is heated by four pairs of gas burners. The fuel is supplied to the burners via gas nozzles with an exit diameter of 120 mm, which are arranged facing each other at an angle of 90°.

The physical modeling method is based on similarity theory, according to which dimensional physical values can be combined in dimensionless complexes in such a way that the number of complexes would be smaller than the number of values composing these complexes [1, 2]. Furthermore, similarity theory determines the conditions under which the modeling results can be extrapolated to other processes that are similar to the ones studied.

The calculation of the principal parameters for the modeling was carried out according to the method developed by A. A. Sokolov and K. A. Pchelyakov [3].

In accordance with the problem, the following temperature range was chosen for the glass melt: $t_{max} = 1500°C$, $t_{min} = 1370°C$, $\Delta t = 130°C$.

Figure 1 shows the temperature dependence of the kinematic viscosity of the glass melt and the model liquid for the glass melted in glass-melting furnace No. 2 and the temperature relation plot.

We find from the plot that the maximum temperature correlates with the minimum kinematic-viscosity value 0.32×10^{-3} m^2/sec.

The geometric scale is related to the viscosity scale. Based on the following main conditions of the modeling of glass melt convection:

$$\mathrm{Gr} = gl^3/\nu^2 = \mathrm{idem};$$

$$\beta/\Delta t = \mathrm{idem};$$

$$\mathrm{Re} = vl/\nu = \mathrm{idem},$$

we obtain

$$C_l = \sqrt[3]{C_\nu^2}; \quad C_\nu = C_l^{3/2},$$

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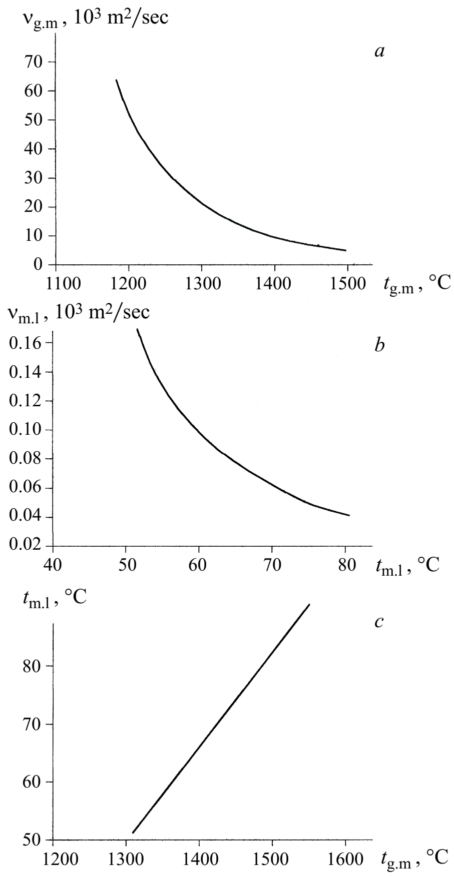

Fig. 1. Temperature-viscosity parameters of glass melt (*a*) and model liquid (*b*); temperature relation plot (*c*).

where Gr is the Grashof number; g is the free-fall acceleration, m/sec^2; l is the geometric size, m; ν is the kinematic viscosity, m^2/sec; β is the volume expansion coefficient, K^{-1}; Re is the Reynolds number; v is the velocity, m/sec; C is the scale.

The scale $C_l = 25$ was chosen for modeling, and then $C_\nu = 125$ (C_l is the linear scale, C_ν is the viscosity scale). Taking these scales into account, we will find the maximum and minimum values of the kinematic viscosity of the model liquid:

$$v^{\mathrm{m}}_{\max} = 0.18 \times 10^{-3}\ \mathrm{m^2/sec};\ v^{\mathrm{m}}_{\min} = 0.026 \times 10^{-3}\ \mathrm{m^2/sec}.$$

The indicated kinematic-viscosity values correlate with the following temperatures of the model liquid: $t^{\mathrm{m}}_{\min} = 48°\mathrm{C}$, $t^{\mathrm{m}}_{\max} = 85°\mathrm{C}$, $\Delta t^{\mathrm{m}} = 37°\mathrm{C}$. The temperature scale: $C_l = \Delta t/\Delta t^{\mathrm{m}} = 130/37 = 3.5$.

The scale of velocity is found based on the condition Re = idem: $C_v = C_\nu/C_l = 5$, and the output scale is found from the condition $C_G = C_\rho C_v C_l = 5937$ (C_ρ is the density scale). The consumption of the model liquid amounts to

$$G_{\mathrm{m}} = G/G_G = 23\ \mathrm{g/min},$$

where G is the furnace output, ton/min.

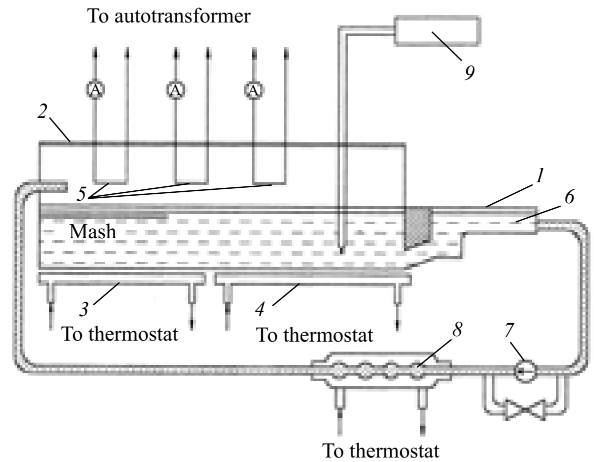

Fig. 2. Experimental device for modeling of glass melt hydrodynamics.

The time scale $C_\tau = \sqrt{C_l} = 5$. Glycerin was used as the model liquid, with LiCl used as an additive.

The model design has to ensure not only the similarity of the thermal and hydrodynamic processes corresponding to the processes in the functioning furnace but also convenience of observation and the ability to measure the main flow parameters: glass melt routes and speed and temperature fields.

The scheme of the model is shown in Fig. 2. The case *1* of the model is made of organic glass 4 mm thick, and the roof *2* is of sheet aluminum. The model is mounted on a special stand. Water-cooled slabs *3*, *4* positioned beneath the bottom of the model are connected to thermostats and correspond to two furnace zones: melting zone and homogenization/clarification zone. The temperature in the thermostats was maintained with an accuracy to 0.5°C. By varying the temperature in the thermostats and the consumption of thermostat liquid, it is possible to regulate the temperature in each zone.

Heating of the model liquid from above was performed by Nichrome heaters *5*, which made it possible to control the heat release level within a wide range. Each Nichrome heater section was connected to an autotransformer. The heat flow was controlled by varying the voltage applied to the heater, and that is how the temperature distribution on the model liquid surface was controlled.

Glass production was simulated by pumping the model liquid from the working tank *6* using the gear pump *7*. The liquid was cooled in the transport pipeline and the chiller *8* to the temperature of the glass melt in the zone below the batch. Thermocouples were connected to the digital voltage meter *9*. The total absolute error of a thermocouple and the digital meter did not exceed 0.5°C, and the relative error amounted to 1%.

The hydrodynamic processes in the furnace model were studied by registering the migration routes of colored indicators introduced into the liquid in the form of a vertical filament employing a special syringe.

The effect of the following factors on the glass melt hydrodynamics was studied in the first stage: position of the maximum-temperature zone (quellpunkt) on the glass melt surface, specific output of glass melt, and height of the spillover threshold.

Specific efficiency (glass melt output) of the furnace. Model studies were conducted within the productivity range of 1500 – 3000 kg/m^2 per day.

When the specific output is equal to 1500 kg/m^2 per day, in addition to the main flows, a circulating flow known as the Schuld wave exists in the zone following the spillover threshold, and another flow exists in the thin surface layer. These latter flows are regarded as undesirable and capable of degrading the thermal homogeneity of the melt. When the output is higher than 1500 kg/m^2 per day, such flows are not registered. An increase in the glass melt output from 2000 to 3000 kg/m^2 per day did not significantly alter the melt hydrodynamics either in the melting zone of the furnace or in the clarification zone. The speed of the glass flow in the bottom layer in the melting zone and the speed of the flows adjacent to the walls in the clarification zone increased (Fig. 3).

Probably, with the specific output exceeding 2000 kg/m^2 per day, it is necessary to provide for a higher concentration of thermal energy in the spillover threshold zone. This can be accomplished, for instance, by installing additional electric heating in front of the spillover threshold and directly behind this threshold (to decelerate the glass melt flow that migrates along the wall from the threshold to the neck).

Quellpunkt position. The main parameters of the furnace performance: glass melt output 2000 kg/m^2 per day, the tank bottom is heat-insulated, melting temperature 1530°C.

The migration of the glass melt in the tank is indicated in Fig. 4 for different positions of the quellpunkt. An analysis of these data first of all reveals a significant effect of the position of the maximum-temperature zone on the glass melt migration. Obviously, special attention should be paid to this factor when searching for the optimum operating conditions for the furnace.

The best option among the three operating modes is the one in which the quellpunkt is located above the threshold or in the direct vicinity of it. In this case, the pouring cycle of the glass melt flows is longer, and the melt flows at the entrance to the clarification zones are more stable.

Threshold height. The height of the spillover threshold in the functioning furnace is 270 mm. The modeling demonstrated that with this threshold height, the reverse current flowing underneath the batch has a small thickness and insufficient speed. When the threshold height was increased to 600 – 700 mm, the reverse-flow thickness amounted to about 1/2 of the melting-tank depth. At the same time, the speed of the flow increased 1.4 – 1.6 times, which ultimately should have a positive effect on the glass melting process.

The second phase of modeling involved determination of the optimum operating mode for a glass-melting furnace

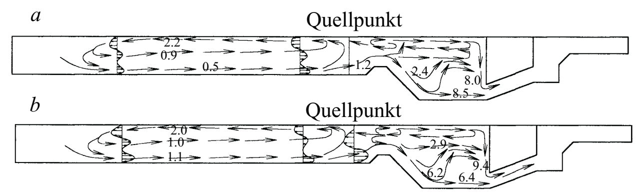

Fig. 3. Glass melt currents in model of glass-melting furnace of capacity 2000 kg/m^2 per day (*a*) and 3000 kg/m^2 per day (*b*). Numbers at the arrows: speed of the flows (m/h).

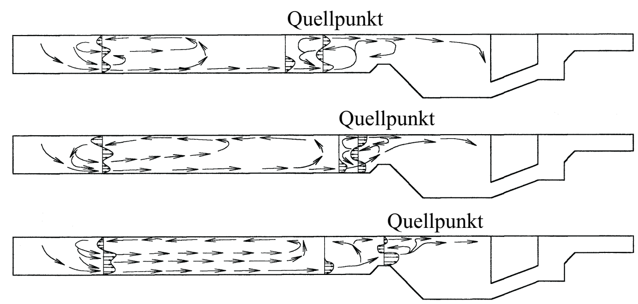

Fig. 4. Glass melt flows in model of furnace with various positions of the quellpunkt.

whose melting tank was divided by the threshold into two parts: the melting and clarification zones.

The optimum operating conditions were chosen based on the following assumptions [4]:

– intense circulatory movement should take place in the melting zone;

– all or a major part of the glass melt should traverse the maximum-temperature zone;

– a stable and clearly expressed quellpunkt should exist in the melting zone;

– the speed of the upper branch of the pouring cycle should be as high as possible.

The experiments showed that the qualitative aspect of the glass melt currents in the furnace significantly depends only on the degree of heat insulation of the furnace bottom. When the bottom is not insulated and the temperature difference across the depth is 120 – 140°C, two circulating flows coexist in the furnace: the pouring flow and the working flow, whose respective thickness amounts to 2/3 and 1/3 of the melting zone depth. Besides, another working current exists near the bottom and is directed toward the charging zone. A low-mobility glass melt layer exists between the pouring and working flows.

Depending on the location of the temperature maximum, the extension of the flows can vary, but on the whole the hydrodynamic picture is preserved. In this way, three flows exist in the melting zone: the upper flow (it is directed underneath the nonmelted batch and maintains the boundary between the batch and the froth), the middle flow (the lower branch of the pouring cycle), and the bottom flow. The middle flow rises in the quellpunkt area and splits into two

branches: one of them completes the pouring cycle, and the second branch moves inside the surface layer toward the tank neck. The bottom flow descends along the vertical wall of the clarification zone and arrives at the working zone.

In the case where the furnace bottom is heat-insulated and the temperature difference across the glass melt depth is about 70 – 80°C, the hydrodynamic situation in the furnace is different. Only one joint pouring cycle exists in the melting zone, the upper flow of which is directed toward the charging zone, and the lower one toward the working zone. The lower flow rises in the quellpunkt zone and splits into two branches, one of which completes the pouring cycle, and the other moves toward the clarification zone. The speed of the bottom glass layers increases 2.5 – 3 times in the case of heat insulation of the bottom, which will make it possible to intensify the melting process.

The study performed resulted in the following conclusions:

– the spillover threshold contributes to increasing the clarification potential of the furnace and decreases the amount of low-mobility glass melt;

– the optimum thermal conditions in this case are accomplished if the quellpunkt is located directly at the threshold or above the threshold;

– the trapezoidal shape of the threshold facilitates the thermal homogeneity of the glass melt and extends the threshold service life;

– the described results of the modeling substantiated the need to insulate the melting zone of the furnace tank; this produces a two-level convection, which makes it possible to identify the quellpunkt with accuracy;

– with the output exceeding 2000 kg/m^2 per day, the number of low-mobility melt sites decreases significantly;

– the hottest glass melt currents circulate near the neck wall;

– it is expedient to increase the threshold height to 0.7 – 0.9 m for rational organization of the flow and intensification of the reverse flow oriented underneath the batch.

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